Lifetimes and Mixing at DØ

Brendan C. K. Casey [a] on behalf of the DØ Collaboration

[a]Department of Physics, Brown University
P.O. Box 1843, Providence. RI 02912, USA

We present results on b hadron lifetimes and mixing using large samples of single and dimuon data collected by the DØ detector operating at the Fermilab Tevatron. We focus on the exciting possibilities available at hadron colliders due to the diversity in produced hadron species and the unprecedented production cross-sections. This is illustrated with benchmark measurements such as lifetime ratios and the B_d mixing frequency. Expectations for key measurements such as the B_s mixing parameters with larger data samples are also discussed.

1. Introduction

Measurements of flavor mixing in neutral meson systems have historically lead to profound insights into physics at energy scales inaccessible to particle accelerators. The discovery of mixing and CP violation in the neutral kaon system [1] lead Kobayashi and Maskawa to predict the existence of a third flavor generation [2]. The discovery of mixing in the B_d system gave the first indication that the top quark is much heavier than the W boson [3]. Finally, mixing induced CP violation measurements in the B_d system have precisely determined the phase of the CP violating top quark coupling Arg$(V_{td}) \sim 24^\circ$ [4,5]. This motivates the study of mixing in the B_s system. A B_s mixing measurement allows a precise determination of the magnitude of the CP violating top coupling through the ratio $|V_{td}/V_{ts}|$ and may lead to the discovery of new physics in $b \to s$ transitions [6].

Lifetime measurements of various b hadron species are ideal laboratories for separating the weak and strong dynamics of heavy hadron decay. Ratios of lifetimes between different hadron species are insensitive to CKM physics and provide a direct measurement of higher order and non perturbative corrections to operator product expansions [6]. Also, measurements of the B_s lifetime using decays to CP eigenstates measures the B_s mixing parameter $\Delta\Gamma_s/\Gamma_s$ which as stated above probes new physics in $b \to s$ transitions [6].

The DØ flavor physics program focuses on the strengths of the DØ detector: Good tracking, vertexing, muon identification, and single and dimuon triggering capabilities. This allows us to collect large samples of semileptonic and $b \to J/\psi X$ decays that are ideal samples for mixing and lifetime studies. More detailed information on the results presented in this paper are available in ref. [7].

The DØ detector is a general purpose spectrometer and calorimeter. Charged particles are reconstructed using a silicon vertex tracker and a scintillating fiber tracker located inside a superconducting solenoid coil that provides a 2 T magnetic field. Photons and electrons are reconstructed using a Uranium sampling calorimeter and scintillating strip pre-shower detectors located outside the solenoid. Jet reconstruction and electron identification are further augmented with a liquid Argon hadronic calorimeter. Muons are reconstructed using a spectrometer consisting of magnetized iron toroids and three super layers of proportional tubes and plastic trigger scintillators located outside the calorimeter.

The DØ trigger is based on a three tier system. The level 1 and 2 muon triggers rely on energy deposited in the muon spectrometer and fast reconstruction of muon tracks. The level 3 trigger performs fast reconstruction of the entire event allowing for invariant mass and impact parameter requirements for particular final states.

2. Lifetimes using $b \to J/\psi X$ Final States

Candidate J/ψ mesons are formed by combining two oppositely charged muon candidates. One muon is required to have a well measured track in both the muon spectrometer and central tracking system. The second is allowed to be a calorimeter MIP associated with a charged track. This leads to a sample of 1.21 million J/ψ mesons in a 225 pb^{-1} data set. Candidate b hadrons are reconstructed by combining the J/ψ with other charged particles in the jet associated with the J/ψ. Final states with similar topologies such as Λ and K^0_S or ϕ and K^{*0} are analyzed in pairs to help control systematics [8].

The Λ_b lifetime has been measured by several experiments using semileptonic decays yielding a word average value significantly lower than the B_d lifetime [9]. Since the final state was not fully reconstructed in these measurements, there are uncertainties due to the reconstructed boost of the Λ_b and the purity of the initial state. A goal of the Tevatron Run II program is to make a precise measurement of the Λ_b lifetime using fully reconstructed decays to the $J/\psi\Lambda$ final state. Our $J/\psi\Lambda$ invariant mass distribution is shown in Figure 1. We observe 52 ± 13 Λ_b events in our 225 pb^{-1} data set. The corresponding signal in the $B_d \to J/\psi K^0_S$ channel is also shown Figure 1. We observe 375 ± 29 B_d candidates in the same data set.

A simultaneous fit to the lifetime and polarization amplitudes in the $B_s \to J/\psi\phi$ channel can be used to measure $\Delta\Gamma_s/\Gamma_s$ [6]. Figure 2 shows the $J/\psi\phi$ invariant mass distribution for B_s candidates and the $J/\psi K^{*0}$ invariant mass distribution for B_d candidates. We observe 403 ± 38 B_s candidates and 1857 ± 72 B_d candidates in our 225 pb^{-1} data set.

We extract lifetimes by performing a fit to the transverse proper flight length distribution. The signals are modeled as exponentials convolved with Gaussian resolution functions. The backgrounds are modeled as Gaussian resolution functions for the prompt components and exponential tails for heavy flavor components. In most cases, two dimensional fits are applied including the invariant mass spectrum to constrain the signal

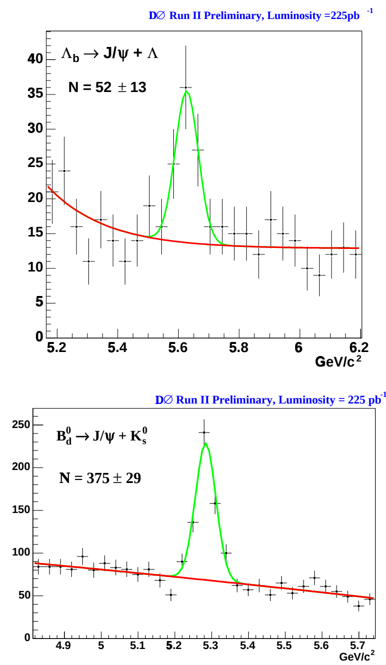

Figure 1. The $m(J/\psi\Lambda)$ distribution for Λ_b candidates (top) and the $m(J/\psi K^0_S)$ distribution for B_d candidates (bottom).

to background fractions and background parameterizations. Example distributions are shown in Figure 3 for the inclusive $b \to J/\psi X$ sample and the $B^+ \to J/\psi K^+$ final state. The lifetimes for several b hadron species determined using ~ 120 pb^{-1} are listed in Table 1. These results are in good agreement with the world average values [9].

3. Lifetimes using Semileptonic Decays

We identify semileptonic decays by requiring the presence of a muon reconstructed in the central tracking system and the muon spectrometer with transverse momentum p_T greater than 2 GeV/c and total momentum p greater than 3 GeV/c. We form a sample enriched with B^+ and B_d decays by requiring the presence of a $\bar{D}^0$ associated with the muon. The $\bar{D}^0$ is reconstructed in the $K^+\pi^-$ channel from tracks in the same

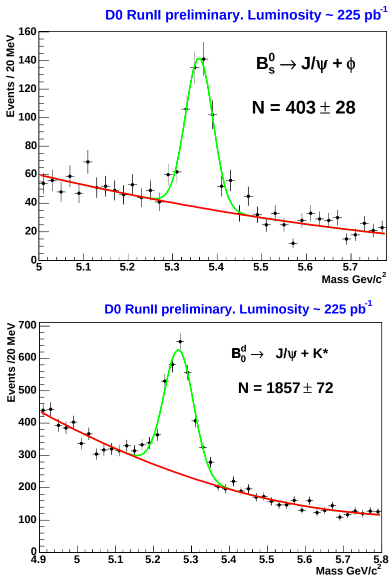

Figure 2. The $m(J/\psi\phi)$ distribution for B_s candidates (top) and the $m(J/\psi K^{*0})$ distribution for B_d candidates (bottom).

jet as the muon. The kaon and muon are required to have opposite charge. Loose impact parameter requirements are applied to the kaon and pion and $\bar{D}^0$ flight length significance requirements are applied to reduce prompt backgrounds. These requirements bias the B flight length distribution but do not bias ratios of flight lengths. The $K^+\pi^-$ invariant mass distribution is shown in Figure 4. We reconstruct approximately 436 $\bar{D}^0$ candidates per pb^{-1}. A D^{*-} sample is constructed by associating a $\bar{D}^0$ candidate with a slow pion and reconstructing the mass difference $\Delta m = m(K^+\pi^-\pi^-) - m(K^+\pi^-)$, also shown in Figure 4. We reconstruct approximately 100 D^{*-} candidates per pb^{-1}.

The D^{*-} data sample is dominated by B_d semileptonic decays while the $\bar{D}^0$ sample is dominated by B^+ semileptonic decays after removing the D^{*-} candidates. Based on measured semileptonic branching fractions [9] and isospin relations, the expected sample composition is 86% B_d, 12% B^+, and 2% B_s for the D^{*-} sample and 82% B^+, 16% B_d, and 2% B_s for the $\bar{D}^0$ sample. Given our large semileptonic data sample, we will be able to perform more precise measurements of all semileptonic b decays in the near future. As an example, we have begun a study of $B \to D^{*-}\pi^+ X \mu^+\nu_\mu$ decays. We clearly observe the $\bar{D}_1^0$ and $\bar{D}_2^{*0}$ intermediate states in the $D^{*-}\pi^+$ invariant mass distribution shown in Figure 5.

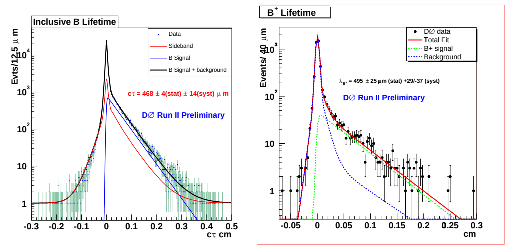

Figure 3. The reconstructed proper decay length distributions for inclusive $b \to J/\psi X$ candidates (left) and $B^+ \to J/\psi K^+$ candidates (right).

Table 1
DØ lifetime results for b hadrons using final states containing a J/ψ meson based on the ~ 120 pb^{-1} data set.

Mode	DØ lifetime (ps)
$b \to J/\psi X$	$1.562 \pm 0.013 \pm 0.045$
$B^+ \to J/\psi K^+$	$1.650 \pm 0.083^{+0.096}_{-0.123}$
$B_d \to J/\psi K^{*0}$	$1.51^{+0.19}_{-0.17} \pm 0.20$
$B_d \to J/\psi K^0_S$	$1.56^{+0.32}_{-0.25} \pm 0.13$
$B_s \to J\psi\phi$	$1.19^{+0.19}_{-0.16} \pm 0.14$

The B decay vertex is reconstructed in the transverse plane by first reconstructing the $\bar{D}^0$ vertex and extrapolating the $\bar{D}^0$ momentum vector to its intersection with the muon track. The boost is reconstructed using the transverse momentum of the $\bar{D}^0 + \mu^+$ system from which we create a visible proper decay length defined as

$$c\tau_{vis} = L_{xy} \times m_B / p_T(\bar{D}^0\mu^+)$$

where L_{xy} is the transverse decay length in the

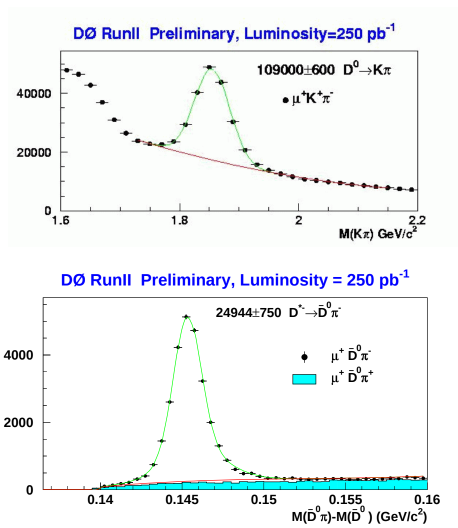

Figure 4. The $m(K^-\pi^+)$ distribution for $B \to \bar{D}^0 X \mu^+ \nu_\mu$ candidates (top) and the Δm mass difference distribution for $B \to D^{*-} X \mu^+ \nu_\mu$ candidates (bottom).

laboratory frame. Boost correction functions are determined from Monte Carlo (MC) for each final state considered to account for the momentum of all other B daughters besides the $\bar{D}^0$ and muon.

We extract the B^+/B_d lifetime ratio by performing a χ^2 fit to the ratio of D^{*-} to $\bar{D}^0$ yields determined in bins of $c\tau_{vis}$. The $c\tau_{vis}$ variable is reconstructed using only the $\bar{D}^0$ and muon information for both samples and the yield is extracted from the $m(K^+\pi^-)$ distribution for both samples. Therefore the ratio of reconstruction efficiencies for the two samples is independent of $c\tau_{vis}$.

The expected value of the χ^2 is a function of the lifetime ratio, the B_d lifetime which is fixed to the world average value [9], the sample compositions, boost corrections, and resolution functions. The yield ratio as a function of $c\tau_{vis}$ is plotted in Figure 6. The results of the χ^2 fit are overlayed. The resulting lifetime ratio is

$$\tau(B^+)/\tau(B_d) = 1.093 \pm 0.021 \pm 0.022$$

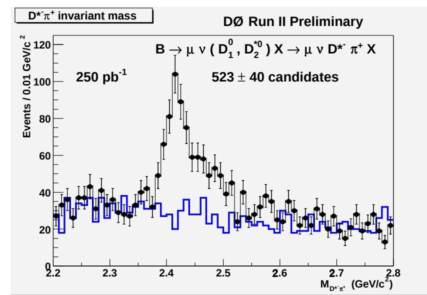

Figure 5. The $m(D^{*+}\pi^-)$ invariant mass distribution for $B \to D^{**0} X \mu^+ \nu_\mu$ candidates.

with a $\chi^2/NDF = 4.0/5$. This is in good agreement with the world average value of 1.086 ± 0.017 [9].

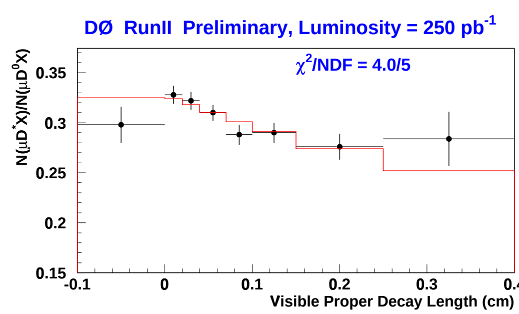

Figure 6. The ratio of D^{*-} to $\bar{D}^0$ yields in semileptonic B decays as a function of the visible proper decay length.

4. Mixing using Semileptonic Final States

There are four major ingredients to time-dependent mixing measurements. The first two are the isolation of a relatively pure sample of neutral B mesons and the reconstruction of the proper time distribution of the B meson. These have been demonstrated above with our precision measurement of the B^+/B_d lifetime ratio. The other main ingredients are determining the flavor of the B meson at its production time, known as flavor tagging, and the extraction of the mixing frequency from the time evolution of samples where the flavor at the decay matches the flavor at production (unmixed sample) and where the flavor at decay is opposite the flavor at production (mixed sample).

We currently employ three techniques to tag the flavor of the reconstructed B meson at production. Two opposite side tagging techniques rely on determining the the flavor of the other b quark in the event by studying its decay products. The muon tag algorithm searches for a muon produced by the semileptonic decay of the other b quark in the event where the charge of the muon determines the flavor of the parent b quark. The jet charge algorithm reconstructs a momentum weighted charge of tracks in the opposite hemisphere of the reconstructed B meson in an attempt to reconstruct the charge, and thus the flavor, of the parent b quark.

The third technique, referred to as same side tagging, attempts to determine the flavor of the reconstructed B meson at production by examining particles associated with the initial fragmentation of the b quark. For instance, a $\bar{b}$ quark that hadronizes into a B_d meson must pop a $d\bar{d}$ pair from the vacuum. The extra $\bar{d}$ quark will in many cases hadronize into a π^+ meson whereas an initial b quark would have lead to a π^- meson.

We define the tagging power as ϵD^2 where ϵ is the efficiency to have tagging information for a reconstructed B meson and the dilution D is the probability that the tag is correct. Using both fully reconstructed $B^+ \to J/\psi K^+$ decays and semileptonic decays, we estimate the tagging power to be approximately 1% for each tagging algorithm. We note that better performance is expected once information from multiple tagging algorithms is combined and more algorithms are added.

To extract the B_d mixing frequency Δm_d we build on the success of the lifetime ratio measurement. The production flavor of the B_d enriched D^{*-} sample is determined first using only the muon algorithm. We then extract the yields of mixed and unmixed samples by fitting the D^{*-}-$\bar{D}^0$ mass difference distributions in bins of $c\tau_{vis}$. A χ^2 fit similar to the fit discussed above is applied to the asymmetry distribution

$$\frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})}.$$

The asymmetry distribution is plotted in Figure 7 with the results of the χ^2 fit overlayed. The resulting mixing frequency is

$$\Delta m_d = 0.506 \pm 0.055 \pm 0.049 \text{ ps}^{-1}$$

again, in good agreement with the world average value $\Delta m = 0.502 \pm 0.007 \text{ ps}^{-1}$ [9]. The measured dilution for the muon tag is $D = 0.46 \pm 0.04$. Systematic studies are still in progress for the mixing measurement using the jet charge and same side tagging algorithms.

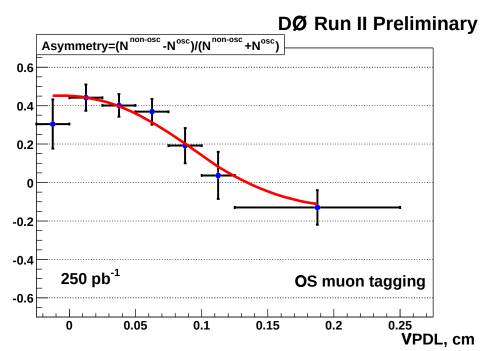

Figure 7. The asymmetry between unmixed and mixed B_d semileptonic decays as a function of the visible proper decay length.

4.1. The Road to B_s Mixing

The next step is to apply the above techniques to a B_s enriched semileptonic sample and extract a value or lower limit on the B_s mixing frequency Δm_s. To enrich the sample, we associate the muon with a D_s^- meson. The $\phi\pi^-$ invariant mass distribution showing clear D^- and D_s^- peaks is plotted in Figure 8. We reconstruct 9481 ± 253

D_s^- mesons in 250 pb^{-1}. Work is in progress to incorporate several more D_s^- final states such as $K^{*0}K^-$ and $K_S^0K^-$ that will lead to large increases in our B_s sample. We have also made significant progress on reconstructing hadronic B meson decays in the hemisphere opposite of the semileptonic decay that triggered the event.

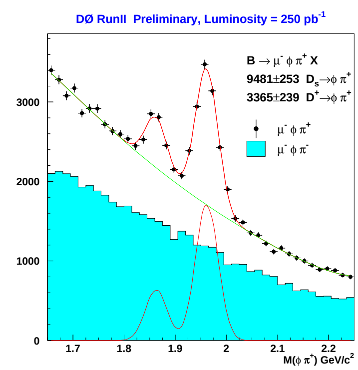

Figure 8. The $m(\phi\pi^-)$ distribution for $B_s \to D_s^- X \mu^+ \nu_\mu$ semileptonic decay candidates.

While the opposite side tagging algorithms are essentially equivalent for the reconstructed B_d and B_s samples, the same side tagging algorithm can be improved using kaon identification since the relevant fragmentation particle is a charged kaon instead of a charged pion. We are currently investigating using dE/dx information from our silicon detector to distinguish kaons from pions. We expect good separation for the low momentum particles associated with fragmentation.

Since a B_s mixing frequency measurement requires excellent vertex resolution, we are adding a rad-hard inner layer of silicon to our tracking system in Summer 2005 that will significantly improve our vertex resolution. The binning methods that were successfully employed for the B_d analysis are also being adjusted to account for the faster B_s mixing frequency and the degradation in the resolution due to the boost correction at large $c\tau_{vis}$ values. With all the above ingredients in place, we expect to have a competitive B_s mixing limit with the current data set.

To conclude, we gratefully acknowledge that the Tevatron has had an excellent year in terms of both peak and delivered luminosity and is on track to double the data sets available to the DØ and CDF experiments every year for the remainder of the Run II program. By performing benchmark measurements such as the B^+/B_d lifetime ratio and the B_d mixing frequency, we have clearly demonstrated that DØ has a competitive flavor physics program which will only get better as more semileptonic channels, hadronic channels, and neutral particles are added to our list of final states. This data is all on tape and it is only a matter of time before it is extracted offline. We have demonstrated the necessary ingredients to perform precision measurements of several key parameters inaccessible to experiments operating at the Υ(4S) such as the Λ_b to B_d lifetime ratio, and the B_s mixing parameters $\Delta\Gamma_s/\Gamma_s$ and Δm_s. We are looking forward to the possible discovery of new phenomena in the flavor sector.

REFERENCES

1. J.H. Christenson *et al.*, Phys. Rev. Lett. **13**, 138 (1964).
2. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
3. H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. **B192**, 245 (1987).
4. K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **87** , 091802 (2001).
5. B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. Lett. **87** , 091801 (2001).
6. For a detailed review, see K. Anikeev *et al.*, FERMILAB-Pub-01/197, hep-ph/0201071 (2001) and references therein.
7. http://www-d0.fnal.gov/Run2Physics/WWW/results/B/b.htm
8. Inclusion of charge conjugate states is implied throughout the text.
9. S. Eidelman *et al.* (Particle Data Group), Phys. Lett. **B592** , 1 (2004).